

Higgs to $\mu\bar{\tau} + \tau\bar{\mu}$ Decay in Supersymmetry without R-parity

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In this short letter, we report on lepton flavor violating Higgs decay into $\mu\bar{\tau} + \tau\bar{\mu}$ under the scheme of a generic supersymmetric standard model without R-parity and list important combinations of R-parity violating parameters which can give significant branching ratios in experimental accessible region. We impose other known experimental constraints on the model parameters, considering both with and without a sub-eV neutrino masses bound on mass contributions from the R-parity violating parameters. In our analysis, the branching ratio of $h^0 \rightarrow \mu\bar{\tau} + \tau\bar{\mu}$ can exceed 10^{-5} within admissible parameter space, while 10^{-2} is possible when the sub-eV neutrino masses bound is lifted.

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I. INTRODUCTION

In standard model (SM), lepton number of each flavor is separately conserved. However, it is well known now from the observation of neutrino oscillation experiments that lepton flavor conservation should be violated [1], which also gives hints of new physics beyond the standard model. Therefore, various lepton flavor violating (LFV) processes have gotten much attention and been analyzed. For example, in the framework of supersymmetry, which is no doubt the most popular candidate theory for physics beyond SM, flavor violating processes such as $\tau \rightarrow \mu\gamma$, $\tau \rightarrow \mu X$, $\tau \rightarrow \mu\eta$ and $\tau \rightarrow \mu\mu\mu$ etc. are discussed in minimal supersymmetric standard model (MSSM) [2] and other supersymmetric extensions [3, 4]. Specifically, for LFV Higgs to $\mu\bar{\tau} + \tau\bar{\mu}$ decay which we put our focus on in this letter, has also been studied generally in the general two Higgs doublet model [5], which allow lepton flavor violation, and in the MSSM with right-handed neutrinos [6]. Though supersymmetry is so far in lack of experimental evidence [7] and hence faces stringent challenges, it is pointed out [8] that there are still rooms for (minimal) supersymmetric standard model to accommodate existing experimental results. For example, large mass spectrum around or beyond 1TeV for majority of supersymmetric particles is possible; by allowing non-universal soft breaking masses or more free parameters can also relax the constraint from experiments.

In many studies of the supersymmetric standard model, a discrete symmetry called “R-parity”, which keeps baryon and lepton number conservation, is often imposed by hand to prevent proton decay and make the lightest supersymmetric particle (LSP) a dark matter candidate. From the theoretical point of view, R-parity is *ad hoc*, not motivated so long as the phenomenological (minimal) supersymmetric standard model is concerned [9]. Otherwise, a generic version of (minimal) supersymmetric standard model without R-parity, which is our focus here, has the advantage of a richer phenomenology and giving neutrino masses and mixings without the need to introduce any extra superfield. Beyond neutrino masses, the key part of R-parity violation of interest is lepton flavor violation, because it can be observed in processes involving only SM particles while SM itself does not give rise to this kind of processes. Higgs to $\mu\bar{\tau} + \tau\bar{\mu}$ decay is our example at hand. In the framework of R-parity violating (RPV) supersymmetry, there have been some studies [10–12] on the issue of lepton flavor violation. However, such studies either were limited to particular types of R-parity violation or did not study Higgs to $\mu\bar{\tau} + \tau\bar{\mu}$.

Recently both ATLAS and CMS reported discovery of a boson state with mass near 125-126 GeV [13, 14] while the Tevatron CDF and D0 collaborations are observing a statistically significant excess in their $\bar{b}b + W$ or $\bar{b}b + Z$ channels [15]. The boson is essentially compatible with a SM-like Higgs, while more data is needed to fully pin down its nature. The flavor violating decay $h^0 \rightarrow \mu\bar{\tau} + \tau\bar{\mu}$ is of particular interest at this moment.

In this short letter, we present the first results of a comprehensive study on the generic supersymmetric standard model, without R-parity, highlighting cases of most interest. Details of our studies will be reported in another publication [16].

In following section, we summarize the basic formulation and parameterization of the generic supersymmetric standard model. The neutral scalar mass matrix is particularly discussed, including the key quantum corrections up to two-loop order. Then we sketch our calculations and present our numerical results in section 3. Note that during our analysis we made no assumptions on RPV parameters hence not losing general validity while keeping Higgs and the mass spectrum of the other particles within experimental constraints. Finally, we conclude this letter and give an account of upcoming works in the last section.

II. GENERIC SUPERSYMMETRIC STANDARD MODEL (WITHOUT R-PARITY) AND HIGGS MASS MATRIX

With the superfield content of the MSSM, the most general renormalizable superpotential can be written as

$$W = \epsilon_{ab} \left[\mu_\alpha \hat{H}_u^a \hat{L}_\alpha^b + h_{ik}^u \hat{Q}_i^a \hat{H}_u^b \hat{U}_k^C + \lambda'_{\alpha jk} \hat{L}_\alpha^a \hat{Q}_j^b \hat{D}_k^C + \frac{1}{2} \lambda_{\alpha\beta k} \hat{L}_\alpha^a \hat{L}_\beta^b \hat{E}_k^C \right] + \frac{1}{2} \lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C \quad (1)$$

where (a, b) are SU(2) indices with $\epsilon_{12} = -\epsilon_{21} = 1$, (i, j, k) are the usual family (flavor) indices, and (α, β) are extended flavor indices going from 0 to 3. Note that λ is antisymmetric in the first two indices as required by SU(2) product rules while λ'' is antisymmetric in the last two indices by SU(3)_C. The soft SUSY breaking terms, which can be written as it

follows:

$$\begin{aligned}
V_{\text{soft}} = & \epsilon_{ab} B_\alpha H_u^a \tilde{L}_\alpha^b + \epsilon_{ab} \left[A_{ij}^U \tilde{Q}_i^a H_u^b \tilde{U}_j^C + A_{ij}^D H_d^a \tilde{Q}_i^b \tilde{D}_j^C + A_{ij}^E H_d^a \tilde{L}_i^b \tilde{E}_j^C \right] + \text{h.c.} \\
& + \epsilon_{ab} \left[A_{ijk}^{\lambda'} \tilde{L}_i^a \tilde{Q}_j^b \tilde{D}_k^C + \frac{1}{2} A_{ijk}^\lambda \tilde{L}_i^a \tilde{L}_j^b \tilde{E}_k^C \right] + \frac{1}{2} A_{ijk}^{\lambda''} \tilde{U}_i^C \tilde{D}_j^C \tilde{D}_k^C + \text{h.c.} \\
& + \tilde{Q}^\dagger \tilde{m}_Q^2 \tilde{Q} + \tilde{U}^\dagger \tilde{m}_U^2 \tilde{U} + \tilde{D}^\dagger \tilde{m}_D^2 \tilde{D} + \tilde{L}^\dagger \tilde{m}_L^2 \tilde{L} + \tilde{E}^\dagger \tilde{m}_E^2 \tilde{E} + \tilde{m}_{H_u}^2 |H_u|^2 \\
& + \frac{M_1}{2} \tilde{B} \tilde{B} + \frac{M_2}{2} \tilde{W} \tilde{W} + \frac{M_3}{2} \tilde{g} \tilde{g} + \text{h.c.} ,
\end{aligned} \tag{2}$$

where $\tilde{L}^\dagger \tilde{m}_L^2 \tilde{L}$ is given by a 4×4 matrix with zeroth components. $\tilde{m}_{L_{00}}^2$ corresponds to $\tilde{m}_{H_d}^2$ in MSSM while $\tilde{m}_{L_{0k}}^2$'s give new mass mixings.

The above, together with the standard (gauged) kinetic terms, describe the full Lagrangian of the model. We have four leptonic superfields \hat{L} , which contain the components of fermion doublet as l^0 and l^- , while their scalar partners as \tilde{l}^0 and \tilde{l}^- . For convenience, we choose a flavor basis such that only \hat{L}_0 bears a nonzero vacuum expectation value (VEV) and thus can be identified as the usual \hat{H}_d in the MSSM. However, one should keep in mind that \hat{H}_d now may contain partly the charged lepton states. The parameterization has the advantage that tree level RPV contributions to fermion mass matrices are described completely by the μ_i , B_i , and $\tilde{m}_{L_{0i}}^2$ parameters, which are well constrained to be small even with just very conservative neutrino mass bounds imposed [17, 18]. The tree level mass matrices for the scalar fields also have minimal extra terms from R-parity violation [17].

For the mass matrices for the (colorless) scalars, we have five neutral complex fields, from \hat{H}_u and four \hat{L}_α superfields, and eight charged fields. Explicitly, for the neutral part we write the $(1 + 4)$ complex fields in terms of their scalar and pseudoscalar parts, in the order $(h_u^{0\dagger}, \tilde{l}_0^0, \tilde{l}_1^0, \tilde{l}_2^0, \tilde{l}_3^0)$, to form a full 10×10 (real and symmetric) mass-squared matrix. As for charged scalars, the basis $\{h_u^{+\dagger}, \tilde{l}_0^-, \tilde{l}_1^-, \tilde{l}_2^-, \tilde{l}_3^-, \tilde{l}_1^{+\dagger}, \tilde{l}_2^{+\dagger}, \tilde{l}_3^{+\dagger}\}$ is used to write the 8×8 mass-squared matrix. The exact form of these tree level matrix elements can be found in [17].

With all the RPV terms, the physical scalar states are now mixture of Higgses and sleptons. The RPV terms provide new contribution to scalar mass matrices and hence Higgs mass. In addition, third generation quarks and squarks could play an important role in radiative corrections to the Higgs sector and hence should be included. Accordingly, we implement complete one-loop corrections, from Ref.[19], to matrix elements directly relating to Higgses (CP-even, CP-odd and charged ones as well) during our computation. Moreover,

light Higgs mass issue is quite sensitive and need to be delicately treated, therefore we include an estimation [20] of the key two-loop corrections in light Higgs related elements also ¹. Note that radiative RPV corrections are typically too small to be taken into account, thus we study tree level RPV effects only.

III. THE CALCULATIONS AND NUMERICAL RESULTS

In this section, we describe most important RPV parameter combinations which are expected to have largest branching ratios without violating existing experimental results. There are several different sources which can give constraints on our RPV parameter setting. Among which, the one from indirect evidence of neutrino mass, i.e. $\sum_i m_{\nu_i} \lesssim 1\text{eV}$ [21] is quite crucial. However, since it has not been completely ruled out for neutrinos having mass larger than 1eV, we give some comments on branching ratios as reference under the condition that neutrino mass constrained only by the solid bounds, i.e. $m_{\nu_e} < 3\text{eV}$, $m_{\nu_\mu} < 190\text{keV}$ and $m_{\nu_\tau} < 18.2\text{MeV}$ [22] as well.

In our numerical computation, we deal directly with mass eigenstates. We put all the tree level mass matrices into the program. In the case of Higgs masses, we include as well the one-loop and two-loop corrections to relevant mass matrix elements as mentioned in section 2. The mass of the Higgses (and other sparticles) needed in our analysis are obtained by diagonalizing corresponding mass matrix numerically. The necessary amplitudes of tree and one-loop Feynman diagrams ² and relevant effective couplings in the model are derived analytically by hand. By encoding the derived analytical formulas of the decay amplitudes into the numerical program, values of total amplitude and hence decay rate can be obtained. In the computation of the total decay width of light Higgs, we include all significant decay channel such as $\bar{b}b$, $\tau^-\tau^+$, WW^* , ZZ^* , $\gamma\gamma$, and gg , as well as the RPV decay $h^0 \rightarrow \mu\bar{\tau} + \tau\bar{\mu}$. With the RPV partial decay width rate for the channel and total decay width, the branching ratio can be obtained.

During numerical analysis, following restrictions and assumptions are used: $|\mu_0|$, $|A_u|$,

¹ Higgses mix with sleptons via RPV terms, but we can still identify Higgses out of other sleptons due to the foreseeable smallness of RPV parameters.

² During numerical computation of Feynman diagrams, *LoopTools* package is used for the evaluation of loop integrals [23].

$|A_d|$ and $|A^\lambda| \leq 2500\text{GeV}$; A_e is set to be zero since its influence is quite small and negligible; $\tilde{m}_E^2 = \tilde{m}_L^2$ (without zeroth component) $\leq (2500\text{GeV})^2$ with off-diagonal elements zero; $\tan \beta$ ranges from 3 to 60; heavy Higgs/sneutrino and charged Higgs/slepton mass is demanded to be above 200GeV. As discussed before, ATALS and CMS data [13, 14] are pointing out a Higgs-like boson with a mass around 125-126 GeV. After including the uncertainties on the experimental Higgs mass and loop corrections estimation to Higgs mass matrix in program, we allow the light Higgs mass to be in the range of 123 to 127GeV. For simplicity, we use the relation $M_2 = \frac{1}{3.5}M_3 = 2M_1$ between three gaugino masses and the condition that squarks of the first two families cannot be lighter than about $0.8M_3$. Therefore we take soft supersymmetry breaking scalar masses $\tilde{m}_Q^2 = \tilde{m}_U^2 = \tilde{m}_D^2 = (0.8M_3 \times \text{identity matrix})^2$ for simplicity and $M_2 \leq 2500\text{GeV}$ as boundary for analysis. The parameter setting is in accordance with the gravity-mediated supersymmetry breaking picture [24], for instance. We are interested in using a concrete setting that is compatible with known constraints but not otherwise too restrictive, to illustrate what we expect to be more generic features of the RPV signature. Besides, to prevent B_i from being unreasonably large, we set by hand 1% of B_0 as upper bound in the circumstance of extraordinary loose or no available experimental bounds.

We highlight below the most interesting combinations of RPV parameters giving significant contributions to the decays.

A. Contributions from $B_i \mu_j$ combinations

Among all $B_i \mu_j$ combinations, only $B_2 \mu_3$ and $B_3 \mu_2$ are expected to give important contribution to $h^0 \rightarrow \mu \bar{\tau} + \tau \bar{\mu}$ because they contribute already at tree level (see diagram FIG. 1 (Left Panel)) and $B_3 \mu_2$ is enhanced by tau Yukawa coupling y_{e_3} via a term proportional to $y_{e_3} M_2^* B_3 \mu_2^* / [(\mu_0 M_2 - M_W^2 \sin 2\beta) M_s^2]$ thus becomes largest one among all $B_i \mu_j$'s (M_s denotes a generic real scalar mass eigenvalue). It also happens to $B_2 \mu_3$, but with a muon Yukawa y_{e_2} instead. These two combinations get their best values under small μ_0 and M_s^2 as can be seen from the formula.

On the other hand, the values of B_i and $B_i \mu_j$ are highly constrained separately by their loop contribution to neutrino mass matrix [25]; a non-zero μ_j will induce tree level neutrino mass, hence it is constrained. In the meantime, leptonic radiative decays like $\mu \rightarrow e \gamma$ etc.

also give upper bounds on $B_i\mu_j$, say, $|B_2^*\mu_3|$ and $|B_3\mu_2^*| \lesssim 10^{-4} |\mu_0|^3$ [12].

By requiring tree level neutrino mass and all the loop contribution from B_i and $B_i\mu_j$ to neutrino mass matrix elements within 1eV, we can get $\text{B.R.}(B_2\mu_3) \cong 1 \times 10^{-15}$ and $\text{B.R.}(B_3\mu_2) \cong 1 \times 10^{-13}$ at most. In this situation, restrictions by leptonic radiative decays are relatively loose such that we don't need to bother with it.

If we allow neutrino masses being larger than 1eV while making μ_0 large enough to unfasten restrictions by leptonic radiative decays, the main constraint will come from $B_i\mu_j$ loop contribution. By demanding $B_2\mu_3$ and $B_3\mu_2$ contribution to the corresponding neutrino mass terms to be only smaller than 190keV, the possible branching ratio for each combination increases significantly to 9×10^{-6} and 7×10^{-4} , respectively. Note that B_2 or B_3 alone can give contributions to $h^0 \rightarrow \mu\bar{\tau} + \tau\bar{\mu}$ decay as well. Such contributions are included in the $B_i\mu_j$ result (and $B_i\lambda$, B_iA^λ thereafter).

B. Contributions from $B_i\lambda$ combinations

Among all $B_i\lambda$'s, it is obvious that $B_1\lambda_{123}$, $B_1\lambda_{132}$, $B_2\lambda_{232}$ and $B_3\lambda_{233}$ are the most important ones because they can contribute to the amplitudes at the tree level already. This tree level contribution can be approximated by $\mathcal{M}_{\text{tree}} \approx B_i\lambda(\tan\beta \sin\alpha - \cos\alpha)/(\sqrt{2}M_s^2)$ where α is the mixing angle between the two CP-even neutral Higgs.

Table 1. $B_i\lambda$ contributions to branching ratio of $h^0 \rightarrow \mu\bar{\tau} + \tau\bar{\mu}$

RPV Parameter Combinations	With Neutrino Mass $\lesssim 1\text{eV}$ Constraint	With Relaxed Neutrino Mass Constraint
$B_1\lambda_{123}$	1×10^{-5}	4×10^{-5}
$B_1\lambda_{132}$	3×10^{-5}	7×10^{-5}
$B_2\lambda_{232}$	3×10^{-5}	6×10^{-2}
$B_3\lambda_{233}$	3×10^{-5}	3×10^{-2}

The value of B_i is constrained by B_iB_j neutrino mass loops [25], while that of λ by charged current experiments [26]. Generally speaking, increasing supersymmetry breaking slepton mass and gaugino mass leads to heavier charged slepton, sneutrino and neutralino hence raises upper bounds for B_i and λ . Due to the strong dependence upon B_i and λ by tree level amplitude, it is still favorable even though heavy sneutrino tend to suppress the

branching ratio. Besides, μ_0 should not be too small in order to make the product of B_i and λ be below the bounds from leptonic radiative decays, i.e. $|B_1^* \lambda_{132}|$, $|B_1 \lambda_{123}^*|$, $|B_2^* \lambda_{232}|$ and $|B_3 \lambda_{233}^*| \lesssim 1.4 \times 10^{-3} |\mu_0|^2$ [12]. Even under stringent neutrino mass $\lesssim 1\text{eV}$ constraint, we find that the four combinations could give sizeable branching ratios of about 10^{-5} , which is large enough to be possibly probed at LHC experiments.

If we do not impose the sub-eV neutrino mass bounds, $B_1 \lambda_{123}$, $B_1 \lambda_{132}$ and $B_2 \lambda_{232}$ still get constrained by $B_i B_j$ neutrino mass loops, while $B_3 \lambda_{233}$ is limited by our manual “1% of B_0 ” bound. This causes their different magnitude of amplitudes. Comparing with neutrino mass $\lesssim 1\text{eV}$ case, branching ratios from B_1 raise a bit, while that from B_2 and B_3 increase significantly by 3 orders of magnitude and reach about 10^{-2} .

C. Contributions from $B_i A^\lambda$ combinations

The contributions may be quite interesting because this will be like the first experimental signature of the RPV A -parameters, and they are not constrained by the radiative decays [12]. However, A^λ only plays its role in a single loop diagram (FIG. 3 (Left Panel)) via neutral scalar-charged scalar-charged scalar ($h^0 \phi^+ \phi^-$) coupling. It is expected to give important contributions for low charged scalar mass to avoid strong suppression. A^λ do not have experimental constraints³, and can consequently take any value. But B_i is still limited by neutrino mass loops as before. Similar to $B_i \lambda$ case, when considering experimental neutrino mass, different mass constraints induce different magnitude of branching ratios (for $B_1 A^\lambda$ and $B_2 A^\lambda$) while B_3 is constrained by the “1% of B_0 ” bound.

Table 2. $B_i A^\lambda$ contributions to branching ratio of $h^0 \rightarrow \mu \bar{\tau} + \tau \bar{\mu}$

RPV Parameter Combinations	With Neutrino Mass $\lesssim 1\text{eV}$ Constraint	With Relaxed Neutrino Mass Constraint
$B_1 A_{123}^\lambda$	5×10^{-11}	2×10^{-10}
$B_1 A_{132}^\lambda$	5×10^{-11}	2×10^{-10}
$B_2 A_{232}^\lambda$	5×10^{-11}	7×10^{-7}
$B_3 A_{233}^\lambda$	5×10^{-11}	1×10^{-7}

³ Recall that under the parameterization adopted here, the \hat{L}_i superfields all have zero VEV. Hence, A^λ as defined does not contribution, for example, to $b \rightarrow s\gamma$ at one-loop level.

In our setting, branching ratios from $B_i A^\lambda$ can at most reach the order of 10^{-7} . However, if we allow A^λ to be as large as 3.1 TeV (or even higher), branching ratio of the order of 10^{-6} and above is possible. Since decay rate is proportional to amplitude square and hence A^λ square, it is easy to see how branching ratio modifies as A^λ increases as can be seen in Fig. 3 (Right Panel).

IV. SUMMARY

There are different scenarios to achieve LFV Higgs decay in supersymmetric standard model depending on how neutrino masses are implemented. We have shown that even with RPV parameters only, significant contributions to $h^0 \rightarrow \mu\bar{\tau} + \tau\bar{\mu}$ are possible. In our analysis, $B_i \lambda$'s undoubtedly provide largest branching ratios. Even with stringent neutrino mass constraint $\lesssim 1\text{eV}$, several combinations of $B_i \lambda$ can still give branching ratios beyond 10^{-5} which should not be overlooked in future collider experiments. We also listed branching ratios as references in case that the sub-eV neutrino mass is relaxed. Such a case is unlikely but not definitely ruled out.

At the end, we would like to encourage our experimentalist colleagues at CMS and ATLAS to investigate those flavor violating Higgs decays because they may give some complementary informations about lepton flavor violating couplings, which are also relevant for neutrinos physics. Moreover, a typical cross section of MSSM 125 GeV at 8 TeV energy is of the order 10 pb. For $Br(h^0 \rightarrow \mu\bar{\tau} + \tau\bar{\mu})$ of the order 10^{-4} and with a luminosity of the order 10 fb^{-1} , this would lead to 10 raw $\mu\bar{\tau} + \tau\bar{\mu}$ events with almost no SM background. This would get amplified with the 14 TeV energy for future LHC run which may give an even better chance to probe the lepton flavor violating couplings.

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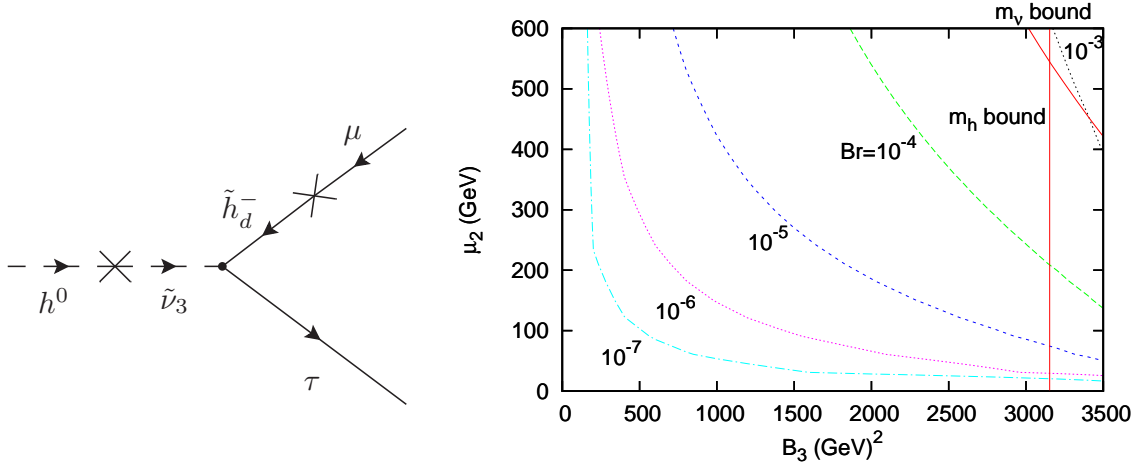


FIG. 1 (Left Panel): An example of tree diagrams. Charged lepton μ transforms into higgsino \tilde{h}_d^- via RPV parameter μ_2 , while light Higgs transforms into sneutrino $\tilde{\nu}_3$ via B_3 . This diagram gives major contribution to $h^0 \rightarrow \tau \bar{\mu}$.

(Right Panel): Branching ratio from $B_3 \mu_2$ as a function of B_3 and μ_2 , with $M_2 = 850\text{GeV}$, $\tilde{m}_{Lii}^2 = \tilde{m}_{Eii}^2 = (800\text{GeV})^2$, $\mu_0 = 2500\text{GeV} = A_u = -A_d$, $\tan \beta = 60$. $m_A \cong 200$ to 320GeV in the permitted region. Solid red line (m_ν bound) comes from demanding 23-element of neutrino mass matrix $<190\text{keV}$, while solid vertical line indicates bound from Higgs mass. If B_3 increases across the m_h bound line, the mass of Higgs (both light and heavy ones) will be below permitted lower bounds.

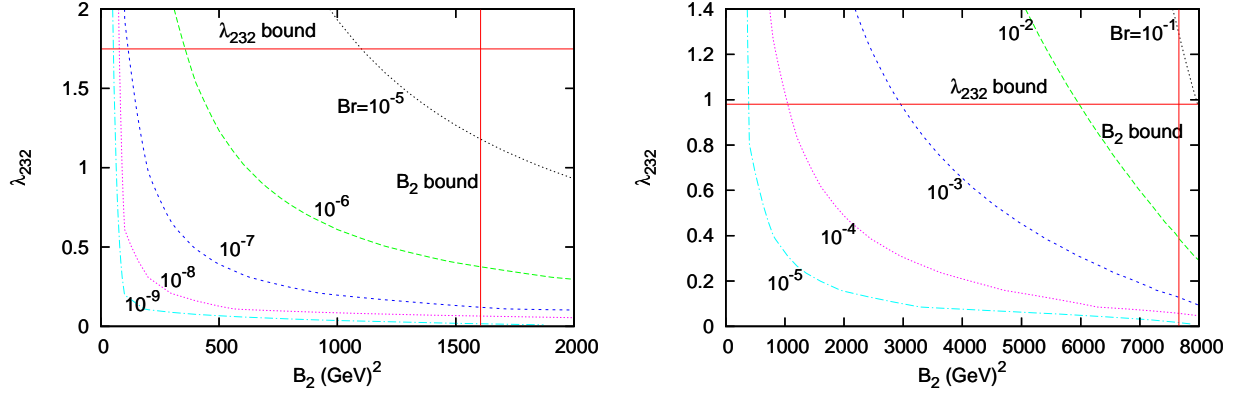


FIG. 2 (Left Panel): Branching ratio from $B_2 \lambda_{232}$, with $M_2 = 2500\text{GeV}$, $\tilde{m}_{Lii}^2 = \tilde{m}_{Eii}^2 = (2500\text{GeV})^2$, $\mu_0 = 1900\text{GeV} = A_u = -A_d$, $\tan\beta = 60$. $M_A \cong 200$ to 205GeV in the permitted region. Upper bounds of B_2 and λ_{232} significantly raised by large soft breaking masses \tilde{m}_{Lii}^2 , \tilde{m}_{Eii}^2 and gaugino mass M_2 . Solid vertical line (B_2 bound) comes from demanding 22-element of neutrino mass matrix $<1\text{eV}$.

(Right Panel): Branching ratio from $B_2 \lambda_{232}$ without sub-eV neutrino mass constraint, with $M_2 = 850\text{GeV}$, $\tilde{m}_{Lii}^2 = \tilde{m}_{Eii}^2 = (1400\text{GeV})^2$, $\mu_0 = 2500\text{GeV} = A_u = -A_d$, $\tan\beta = 60$. $M_A \cong 200$ to 390GeV in the permitted region. Solid vertical line (B_2 bound) comes from demanding 22-element of neutrino mass matrix $<190\text{keV}$.

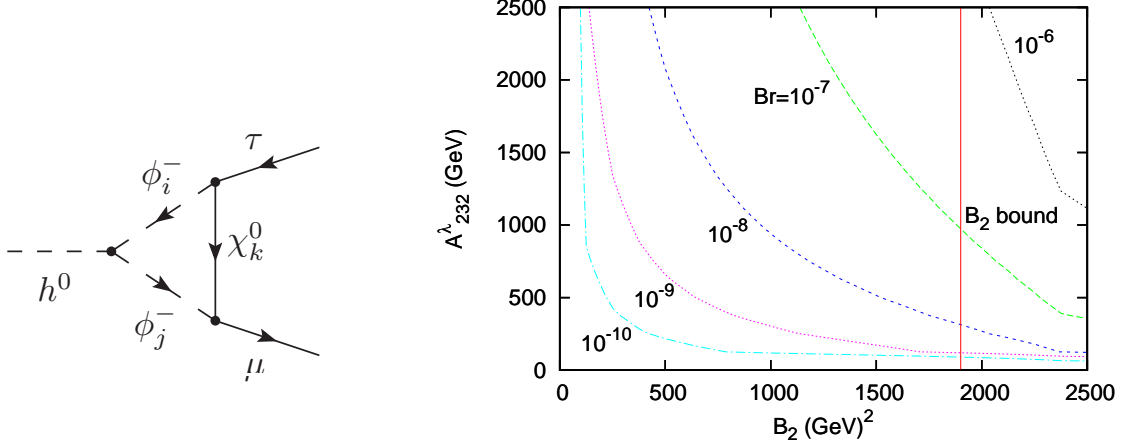


FIG. 3 (Left Panel): The only one-loop diagram in which A^λ has its stage. A^λ participates in via neutral scalar-charged scalar-charged scalar coupling.

(Right Panel): Branching ratio from $B_2 A_{232}^\lambda$ as a function of B_2 and A_{232}^λ , with $M_2 = 850\text{GeV}$, $\tilde{m}_{Lii}^2 = \tilde{m}_{Eii}^2 = (555\text{GeV})^2$, $\mu_0 = 2500\text{GeV} = A_u = -A_d$, $\tan\beta = 60$. $M_A \cong 200$ to 300GeV in the permitted region. Solid vertical line comes from demanding 22-element of neutrino mass matrix $<190\text{keV}$.